MODELLING AND LIVE MEASUREMENTS OF STEP AND TOUCH VOLTAGES AT LV CUSTOMERS IN URBAN AREAS CAUSED BY MV FAULTS

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INTRODUCTION

Earth faults in the medium voltage (MV) grid cause touch and step voltages in the low voltage (LV) grid. Since MV and LV grid share their earthing system at the MV-LV transformer, one might question the safety with respect to LV customers in case of a phase-to-earth fault, occurring in the MV grid. Models and actual measurements in a operating grid are preformed to determine the current distribution and touch voltages. The results show that phase-to-earth faults in urban global earthed areas lead to low source voltages for touching. The models show the current distribution phenomena in a global earthed grid.

BACKGROUND

Questions about the safety due to phase-to-earth fault arise due to the change of the earthing system and the currently used type of MV cable. The change in the earthing system takes place in both the MV and LV grid. The Dutch company Nuon offers a TN earthing system (ES) to its low voltage customers in stead of the former customer installed and maintained TT earthing system. In the MV grid the earthing changes from a system with isolated neutral grid to a system with low-impedance neutral earthing grid. This change is adopted to reduce voltage tresses at the MV components due to the overvoltages appearing during a ground fault. Furthermore insulated XLPE cables are implemented in the MV grid, in stead of the in the past used PILC cables. These changes strongly influence the fault current magnitude and distribution during a phase-to-earth fault in the MV grid and consequently change the magnitude of the touch and step voltages in the LV grid.

For rural areas the safety could easily be guaranteed by local measures [1,2]. In urban areas many paths to the substation grounding and the groundings of the multiple connected MV-LV transformers are present. These paths are the: MV cable sheet and armour, the LV PE conductor and other connections to earth, e.g. streetlight. The LV grid grounding paths will help to lower the step voltages in the LV grid compared to the situation where only the grounding paths in de MV grid are considered.

MODELLING METHOD

Calculations and measurements were carried out to determine whether touch and step voltages in urban areas remained at safe levels. The calculations were made to determine the current distribution and to determine where the maximum voltage rise occur in case of phase-to-earth fault (PEF). On top of that the calculations have to reflect the measurements which have to be carried out in the live public grid without affecting the customers.

In order not to disturb customers during the fault measurements, the earth fault (EF) was obtained by injecting purely a zero-sequence current in the grid. This current was injected at the earthing transformer (ET), i.e. zero-sequence impedance (ZSI), of the substation and returned through a ET located at the EF.

Modelling the real system into extend would be to elaborate, therefore four basic models where constructed. These models consider only the MV grid. The first two models: ‘Model A’ and ‘Model B’, have to give a general concept of the current distribution in a grounded MV cable. The last two models: ‘Actual grid A’ and ‘Actual grid B’, reflect the actual grid under study.

The first model takes into account a MV cable with distributed earth electrodes, see figure 1.

The second model adds one parallel branch approximately half way the length of the MV cable, see figure 2.

To determine where the maximum voltage rise occurs a ZSI is modelled to the earth fault location (EFL) and a zero-sequence source and ZSI is modelled at the substation. The ZSI is successively connected at every earth electrode, to determine the location where the maximum voltage rise occurs. The voltage rise considered, is the source voltage for
touching. This voltage appears during an earth fault between conductive parts and earth when these parts are not being touched. The result are given in figure 6 and 8.

This purely zero-sequence realisation reflects the current ratio distribution through the earthing electrodes during a PEF, because the PEF current in the disturbed phase is the addition of the series current that runs equally through the zero, positive and negative system. The series current during a PEF is in magnitude depending on the series connection of the positive, negative and zero sequence impedance. These symmetrical impedances are proportional to the EFL, i.e. inversely proportional with the magnitude of the series current.

The cable is modelled as a steady-state phasor admittance based on a standard model of a pipe-type cable in EMTP/ATP. Therefore a parallel branch does not incorporate a mutual coupling among parallel cables. The construction of the cable is depicted in figure 3. The earth electrodes resistance at the MV-LV transformer ($R_{EMV-LV}$) is 2$\Omega$ and the resistance to earth of the mesh earth electrode at the substation ($R_{ES}$) is 0.5$\Omega$. Both ET-s had a resistance of 0.72$\Omega$ and a reactance of 7.13$\Omega$.

![Figure 3: Dimensions MV cable.](image)

Given the results of the first two models a simulation was made of the actual grid. The selected earth fault location was at the end of the cable or surrounded by parallel cables. The actual grid is schematically depicted in figure 4 and 5. The lie of the cables meanders through the urban area and is neglected in the figure.

Actual grid A has the earthing transformer at the end of the cable, see figure 4.

![Figure 4: Actual grid A](image)

![Figure 5: Actual grid B](image)

**MODELLING RESULTS**

In figure 6 are given the percentage of the injected 3*zero-sequence current at the neutral earthing of the ET at the substation are given of model one. Per EFL the currents through the distributed earth electrodes at the MV-LV transformer are given.

![Figure 6: Results Model A](image)
The typical zero-sequence impedance of the circuit containing the cable and earth electrodes is shown in figure 7 per fault location.

**Figure 7:** Zero-sequence impedance per fault location

Given the first model one can conclude that:
1. the largest current ratio \( I_{TrMV-LV}/(3I_0) \) to earth is located at the mesh earthing of the substation;
2. a short circuit closer to the substation results in a lower reduction factor of the cable \( r_E \), resulting in a 2.2 decrease the current ratio;
3. an earth fault located at the earth electrode of the MV-LV transformer gives the largest current ratio to earth in respect to the other distributed earth electrodes located at the MV-LV transformer;
4. an earth fault located at the end of a cable gives the largest current ratio to earth in respect earth fault locations;

**Figure 8:** Results Model B

Given the second model one can conclude that:
1. the largest current ratio \( I_{TrMV-LV}/(3I_0) \) to earth is located at the mesh earthing of the substation;
2. a short circuit closer to the substation results in a lower reduction factor of the cable \( r_E \), resulting in a 2.2 decrease the current ratio;
3. the tendency of the current ratio in the paralleled area is decreasing when the EFL is in the paralleled area, and increasing in the pre running cable that feeds the paralleled area;
4. the tendency of the current ratio in the pre running cable when the EF is in the pre running cable is nearly the same in both the paralleled and single cable system.

**Figure 9:** Results Model A and B

Given the models one can conclude that the source voltage for touching is the largest at the location of the earth fault when the earth fault is located at the end of the cable. The voltage is dropping in the paralleled area. Measurement experiment will be designed accordingly.

**MEASUREMENT METHOD**

In newly built quarters of the city Almere, NUON offers safety grounding to customers from the transformer station via an additional conductor in the LV cable. No individual earthing electrodes are required at customer’s houses. In the global earthing approach the grounding of MV and LV systems are coupled at the transformer. Fault currents at the MV grid may propagate into the LV grid. The generated step and touch voltages are kept low by the large spreading of the current over a full quarter. In order to verify the safety of this approach, a special measuring setup has been developed. A small amplitude 60 Hz zero sequence current is injected into the MV cable at the HV-LV substation. The distribution of this current and the resulting voltages can then be determined, with normal 50 Hz power flow present. The design requirements were: an uninterrupted supply to the customers, high selectivity and sensitivity, flexibility and easy installation of current and voltage probes.

The MV grid had an earthing transformer (ET) installed near the HV transformer. The ET neutral connection was wound three times around the core of a welding transformer which had a 60 Hz motor generator to energize its primary. The welding transformer was operated near saturation. A second ET was installed near a MV-LV transformer in the distribution area. The ET neutral was earthed there. Special...
provision there allowed uninterrupted power supply during the installation of the second ET. A zero-sequence current loop is now formed by the MV cable inner conductors and both ETs, in which the MV transformer shield and the soil between the MV transformer and HV substation act as return, in parallel with the many LV connections to earth via all appliances served by the MV-LV transformer.

The frequency of the motor generator could be controlled by an external voltage signal over the limited band of ±0.5 Hz. The generator current was measured by a Pearson 110 probe. A lock-in detector compared the phase of the probe signal with the output of a crystal-controlled 60 Hz oscillator, which on its turn was synchronized to a GPS receiver to obtain a modest frequency stability of better than 1:109 over a day. This is equivalent to an absolute phase deviation of maximally 1 degree per 13 hour. With more modern equipment this stability could have been improved further.

The lock-in d.c. output served as the error signal for the motor generator control circuitry. After some tuning of loop gain and time constants, the phase difference between the injected current and the oscillator remained within four degrees averaged over a 1 second period. As a safety precaution, the current was again measured by a second lock-in. A two-channel instrument registered in-phase and out-of-phase components simultaneously. A data-acquisition system and a computer registered both d.c. outputs of this lock-in over the 50 s. period of a measurement. A no-break supply powered the critical components such as the GPS and the 60 Hz oscillator.

In a van we installed a second set of GPS receiver, oscillator and two-channel lock-in amplifier, powered by a local motor generator, again with a no-break for the critical components. As current sensors we applied clamp-on Fluke current probes and clamp-on air-core Rogowski coils with a 10 cm inner opening to accommodate larger diameter cables of cable bundles. The voltages were measured as difference signal between the neutral/ground connection at the entry point in houses and an 1 m electrode placed at about 10 m distance. Two 1:100 voltage probes preceded and protected an instrumentation amplifier with high common-mode rejection ratio. Both probes were identical to within 1 percent. Since the electrode mentioned before also grounded the low-voltage side of the electronics in the van, one of the voltages at the differential input of the amplifier was close to zero.

In order to reduce the risk of interference, both current and voltage signals went through a low-pass filter before amplification and detection. The d.c. outputs of the lock-in were stored again by a data acquisition system on a computer over the same 50 s. period.

The initial phase difference between both 60 Hz generators was brought to zero at the beginning of a working day. Checks at noon and in the evening showed that both systems remained in phase as expected.

**MEASUREMENT RESULTS**

The measured currents through the electrodes and the voltages of actual grid A are shown in figure 13 and 14.
The measured currents through the electrodes and the voltages of actual grid B are shown in figure 15 and 16.

The measurements show that the voltage drops dramatically in the global earthed quarter. The current though the pre running cable is higher than modelled when the EFL is located in the quarter, because only the MV grid is considered during the model. In the actual grid the earthing system of the LV grid adds more parallel return paths levitating the current though the electrodes connected to the pre running cables.

CONCLUSIONS

Given the models and measurement the conclusion is:

1. phase-to-earth faults in urban global earthed areas leads to low source voltages touching;
2. the models show the current distribution phenomena in a global earthed grid;
3. care should be taken in the feeding cable running solely from substation to the urban area, this should be studied in more detail.

REFERENCES


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